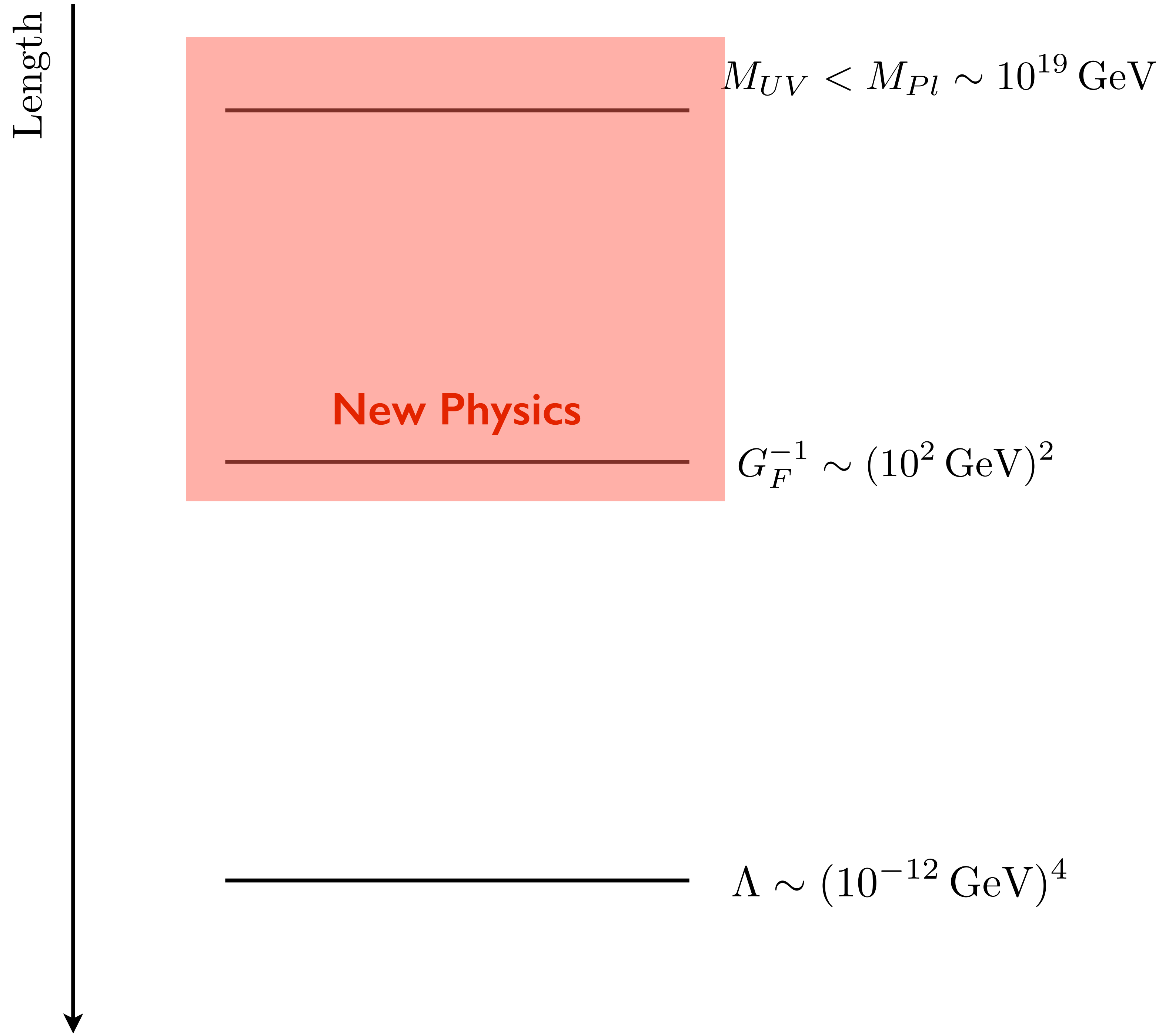
Enviromental selection of the DM density and the low f multiverse axion

work in progress with F.D'Eramo and L.J.Hall

Duccio Pappadopulo - UC Berkeley

Outline

- ★ Enviromental selection of ξ_D by the large scale structure (LSS) boundary.
- ★ Axion DM at the LSS boundary.
- ★ A model with radiative PQ symmetry breaking and the Higgs boson mass.


Length
$M_{UV} < M_{Pl} \sim 10^{19}\,\mathrm{GeV}$
New Physics
$G_F^{-1} \sim (10^2\,\mathrm{GeV})^2$
$\Lambda \sim (10^{-12}\,\mathrm{GeV})^4$

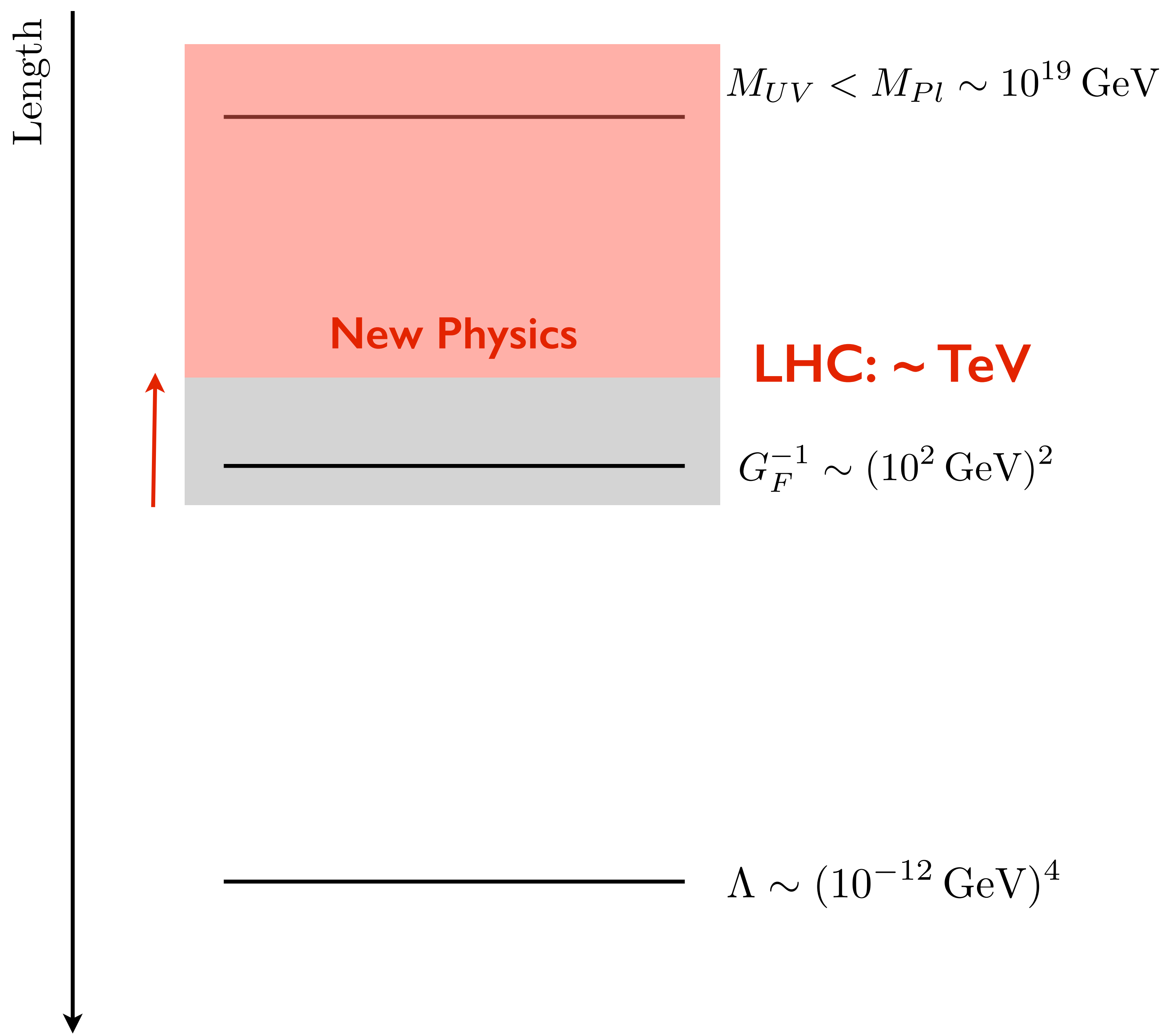
$$\Delta v^2 \sim M_{UV}^2$$

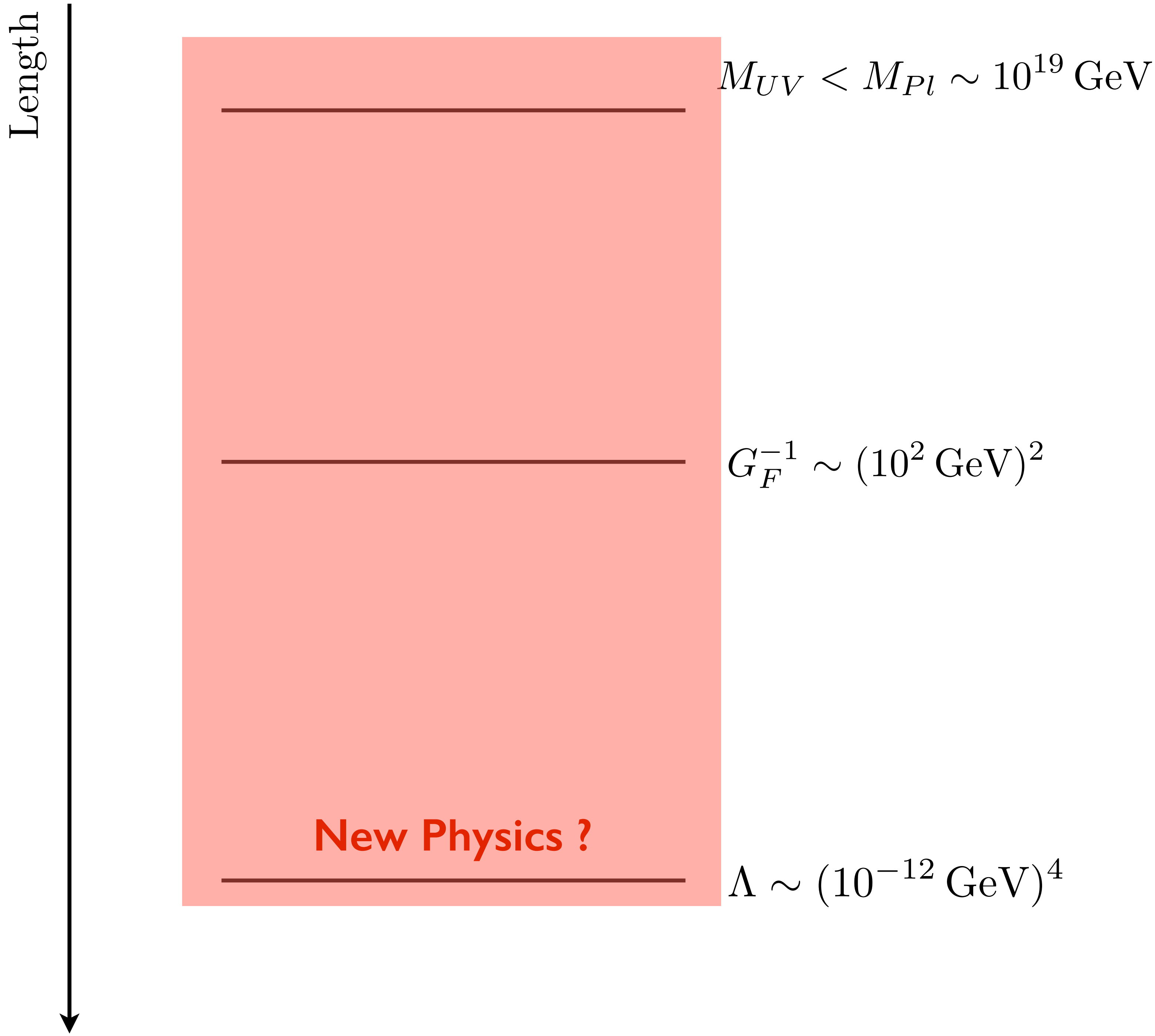
Known dynamical mechanisms to soften the quadratic sensitivity of the weak scale to heavy field theory thresholds.

Supersymmetry

Compositeness

$$\Delta v^2 \sim m_{NP}^2 \log M_{UV}^2$$


Length
$M_{UV} < M_{Pl} \sim 10^{19}\,\mathrm{GeV}$
New Physics
LHC: ~ TeV
$G_F^{-1} \sim (10^2\,\mathrm{GeV})^2$
$\Lambda \sim (10^{-12}\,\mathrm{GeV})^4$


Length
$M_{UV} < M_{Pl} \sim 10^{19}\,\mathrm{GeV}$
$G_F^{-1} \sim (10^2\,\mathrm{GeV})^2$
New Physics ?
$\Lambda \sim (10^{-12}\,\mathrm{GeV})^4$

$$\Delta\Lambda \sim M_{UV}^4$$

NO known and compelling dynamical mechanisms to soften this quartic dependence.

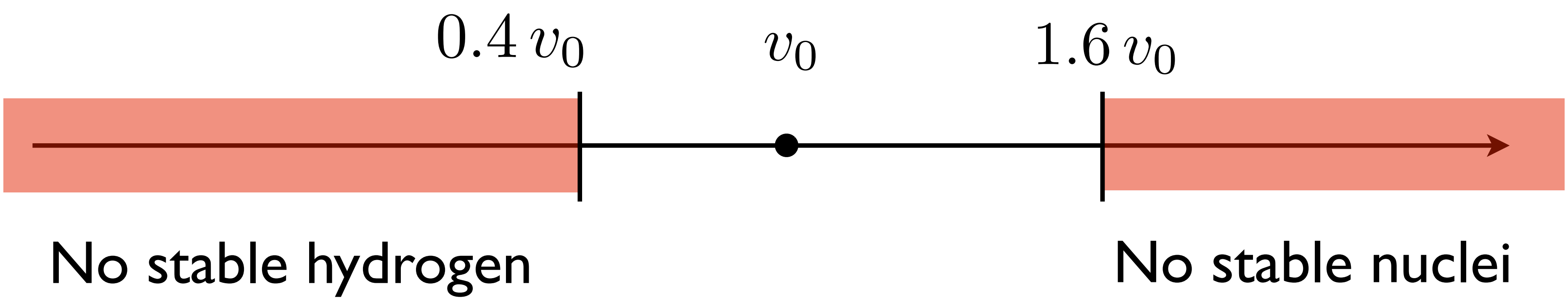
Linked to the possible stabilization of the weak scale

$$\Delta\Lambda \sim m_{NP}^4$$

See Nomura, Shirai ('14)

Scanning the weak scale (and just the weak scale) in the multiverse

The EW vev is subject to the anthtopic requirement of the existence of chemistry.



Agrawal, Barr, Donoghue, Seckel ('97)
Damour, Donoghue ('07)

The Weinberg argument for the Cosmological Constant

Weinberg ('87)
Martel, Shapiro, Weinberg ('98)

Structures below horizon mass at equality grow by the same amount during matter domination

$$\delta \sim \frac{T_{eq}}{T_\Lambda} G(M)\delta_0 \sim \frac{\xi_m}{(\Lambda/\xi_m)^{1/3}} G(M)\delta_0 > 1$$

$$\xi_m \equiv \frac{\rho_m}{n_\gamma}$$

$$\delta_0 \approx 10^{-5}$$

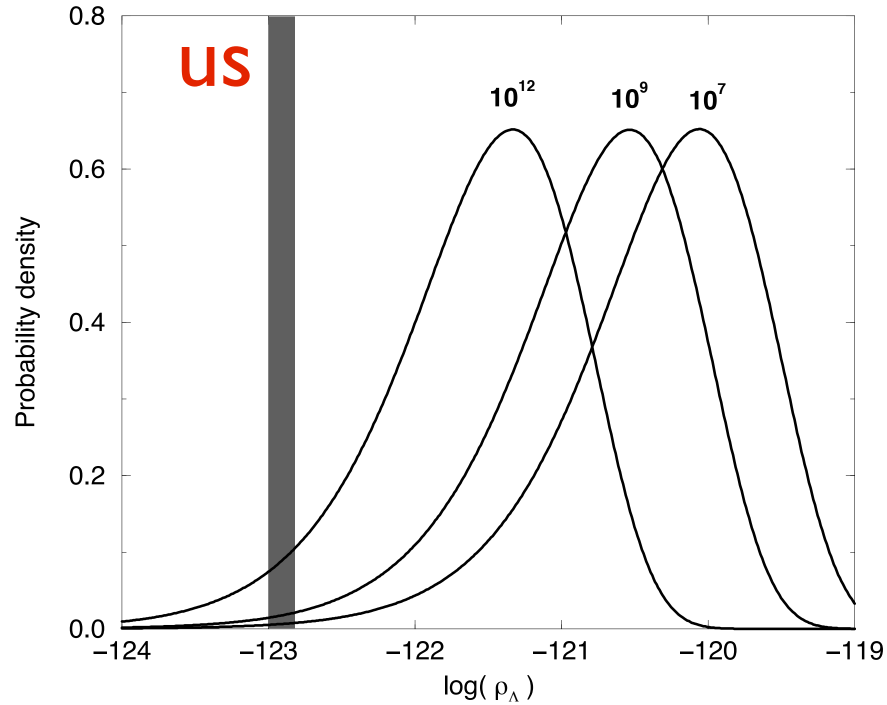
$$M_{eq} = 10^{16} M_\odot \propto \xi_m^{-2}$$

In practice matter should dominate at the redshift where structures start to form

$$\left.\frac{\Lambda}{\rho_m}\right|_{\text{today}} \sim 2 \qquad \text{but} \qquad 1 + z_{SF} \lesssim 10$$

Featureless distribution of the CC around 0

$$dP(\Lambda) \propto d\Lambda$$



$$\delta \sim \Lambda^{-1/3}$$

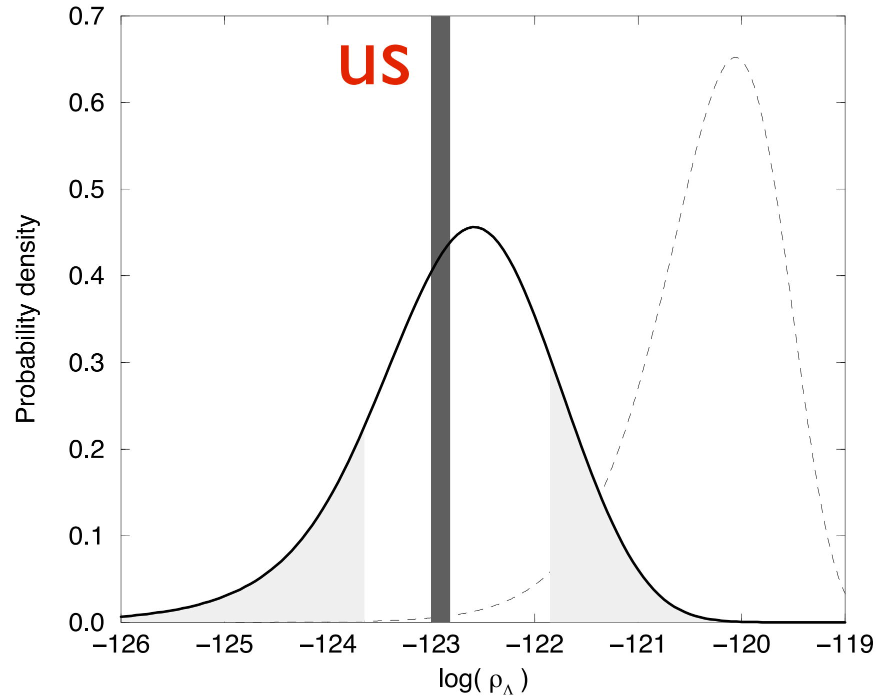
Weight the fraction of virialized baryons

Not a quantitative success

Bousso, Harnik, Kribs, Perez ('07)

Featureless distribution of the CC around 0

$$dP(\Lambda) \propto d\Lambda$$

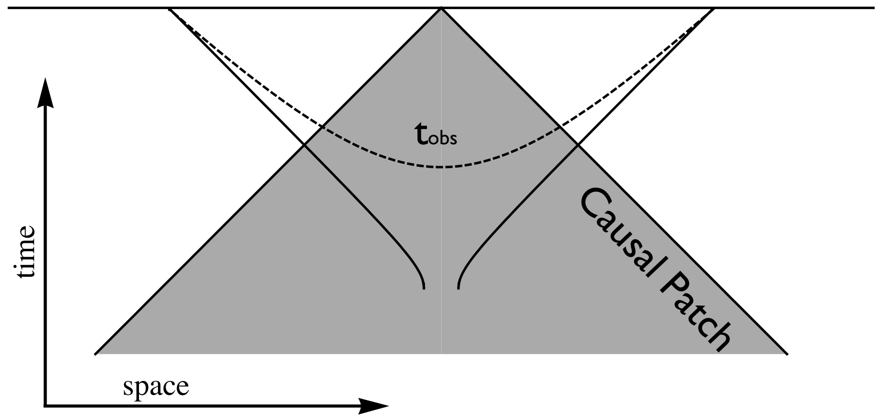


Observers need complexity. Weight by the matter entropy in the causal diamond. No reference to structure formation.

Bousso, Harnik, Kribs, Perez ('07)

Featureless distribution of the CC around 0

$$dP(\Lambda) \propto d\Lambda$$



$$t_\Lambda \equiv \frac{1}{\sqrt{G_N \Lambda}}$$

$$\frac{dp}{d\log t_\Lambda} = \frac{d\tilde{p}}{d\log t_\Lambda} \times n_{\rm obs}(t_{\rm obs}, t_\Lambda) \qquad \begin{cases} t_\Lambda^{-1} & \text{for} \quad t_{\rm obs} < t_\Lambda \\ t_\Lambda^{-1} e^{-3t_{\rm obs}/t_\Lambda} & \text{for} \quad t_{\rm obs} < t_\Lambda \end{cases}$$

$$\frac{d\tilde{p}}{d\log t_\Lambda} \sim t_\Lambda^{-2} \qquad n_{\rm obs}(t_{\rm obs}, t_\Lambda) \sim M_{CP}$$

Bousso, Freivogel, Leichenauer, Rosenhaus ('07)

The CC may be determined by Causal Patch measure. What about the DM matter density?

$$\delta(M) \sim \frac{\min(T_{\rm eq}, T_{\rm hor})}{T_\Lambda} \left(\frac{\xi_b}{\xi_m} e^{-(M_S/M)^{2/3}} + \frac{\xi_D}{\xi_m} G(M) \right) \delta_0$$

$$T_{\rm eq} \sim \xi_m \qquad T_{\rm hor} \sim \frac{k^2}{G_N \xi_m T_\Lambda^2} \qquad T_\Lambda \sim \left(\frac{\Lambda}{\xi_m}\right)^{1/3}$$

$$\lambda_S^{-1} \sim \sqrt{N}\ell \,\Big|_{\rm rec} \sim \sqrt{n_e H \sigma_T}\,\Big|_{\rm rec} \Rightarrow M_S \sim 6 \times 10^{15} M_\odot$$

Before recombination baryon berturbations are Silk damped while after recombination they fall into the CDM potential.

Perturbations grow during matter domination and the growth is halted at the time of CC domination.

The CC may be determined by Causal Patch measure. What about the DM matter density?

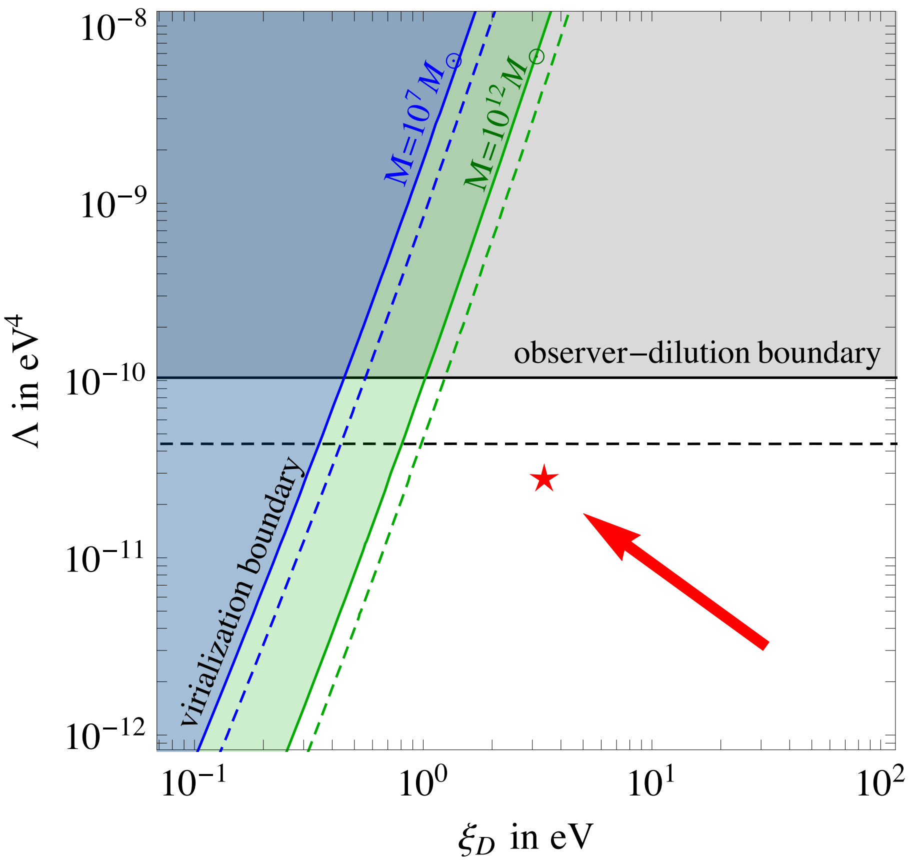
$$\delta(M) \sim \frac{\min(T_{\rm eq}, T_{\rm hor})}{T_\Lambda} \left(\frac{\xi_b}{\xi_m} e^{-(M_S/M)^{2/3}} + \frac{\xi_D}{\xi_m} G(M) \right) \delta_0$$

For modes below the Silk scale

$$\delta(M) \sim \frac{\xi^{1/3}\xi_D}{\Lambda^{1/3}} G(M) \delta_0 \propto \xi_D^{4/3}$$

Assumption:

the vicinity of the LSS boundary is determined by multiverse dynamics



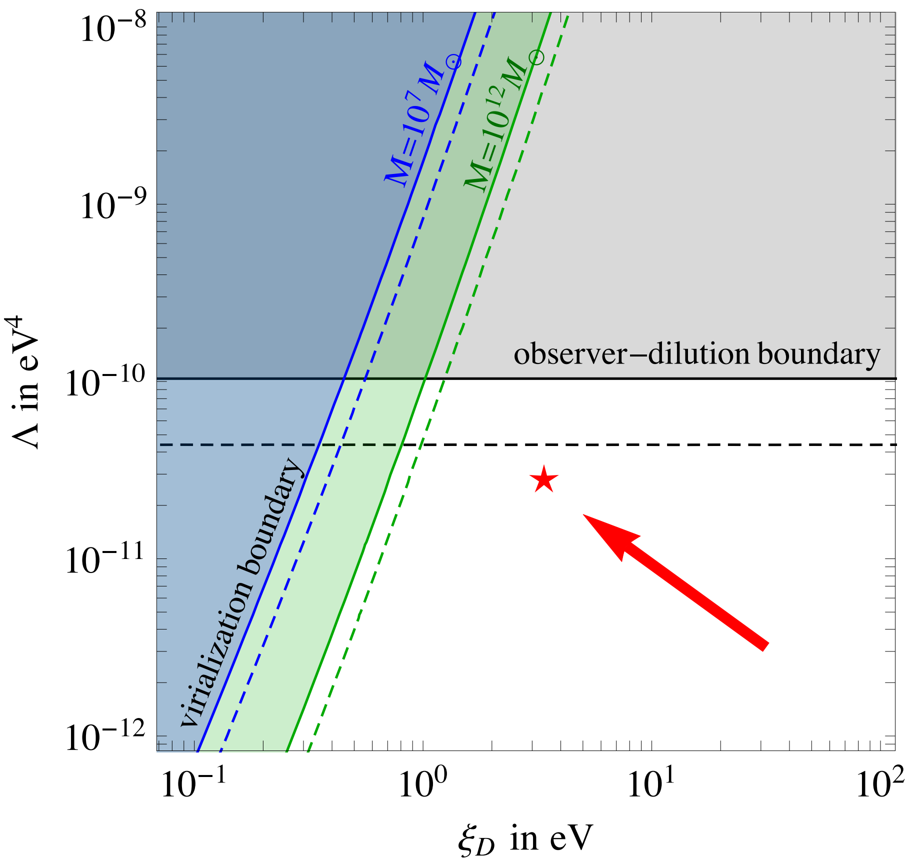
How to draw these boundaries?

$$dP_{CP}(\Lambda) \propto \Lambda^n \times e^{-3(\Lambda/\Lambda_{\rm obs})^{1/2}}$$

$$dP_{LSS}(M;\Lambda,\xi_D) \propto \Lambda^{m_1}\xi_D^{m_2} \times e^{-\alpha(\delta_{m0}/\delta_m)^\beta}$$

$$\begin{cases} M = 10^7 M_\odot : \ (\alpha,\beta) = (-0.03, 1.8) \\ M = 10^{12} M_\odot : \ (\alpha,\beta) = (-0.14, 1.9) \end{cases}$$

5% and 10% reduction of the exponentials

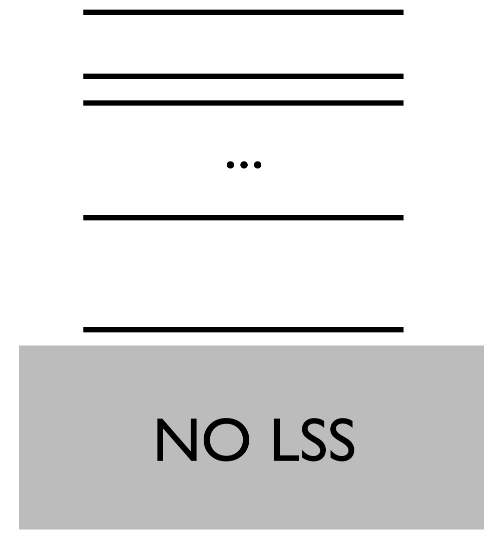


$$M = 10^{(7,12)} : \quad \xi_{5\%} = (0.12, 0.27)\xi_0$$

Consider a SUSY spectrum defined by a fundamental SUSY breaking parameter m, in which the ratios between sparticle masses are roughly fixed

$$dP(\tilde{m}) \sim \frac{\tilde{m}^n}{1+\tilde{m}^2/v^2}\, d\ln\tilde{m}$$

$$\tilde{m} > v : \quad \xi_D \sim \frac{\tilde{m}^2}{M_{Pl}}$$



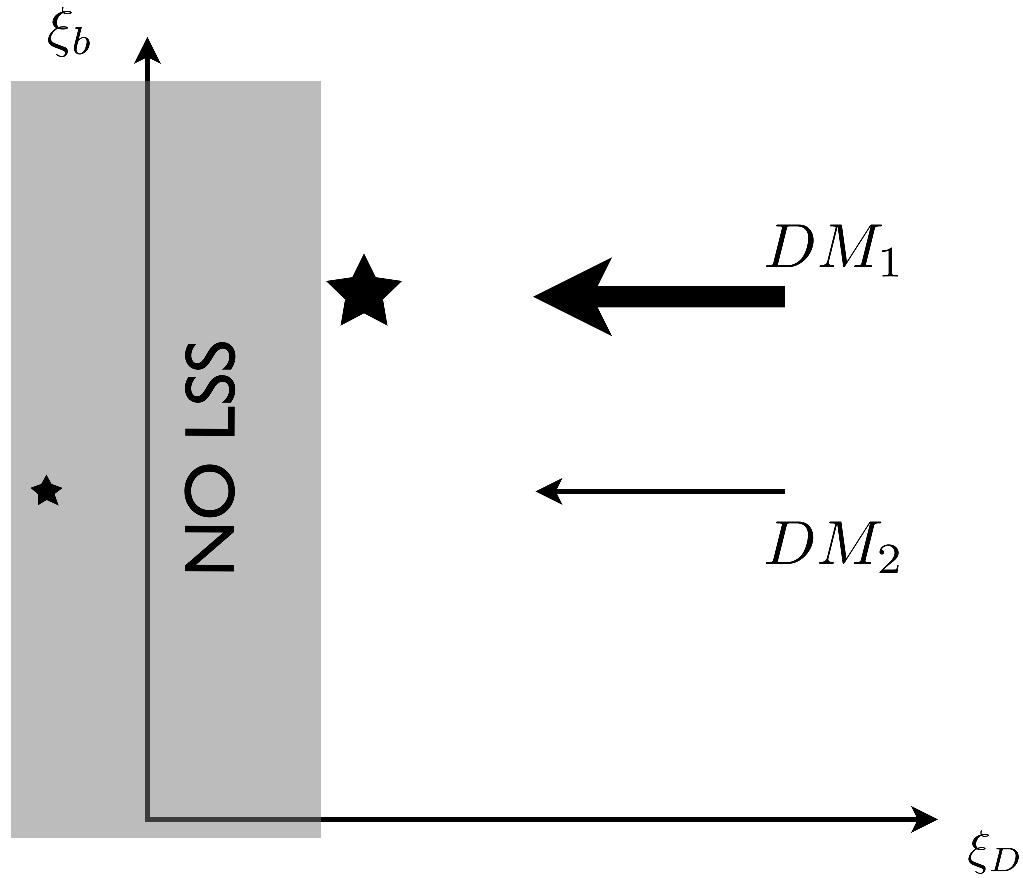
If the theory allows m << v one could hit the Lee-Weinberg limit where

$$\xi_D \sim \frac{v^4}{\tilde{m}^2 M_{Pl}}$$

This is avoided in specific theories (like the MSSM) where v < m or if 0<n<2

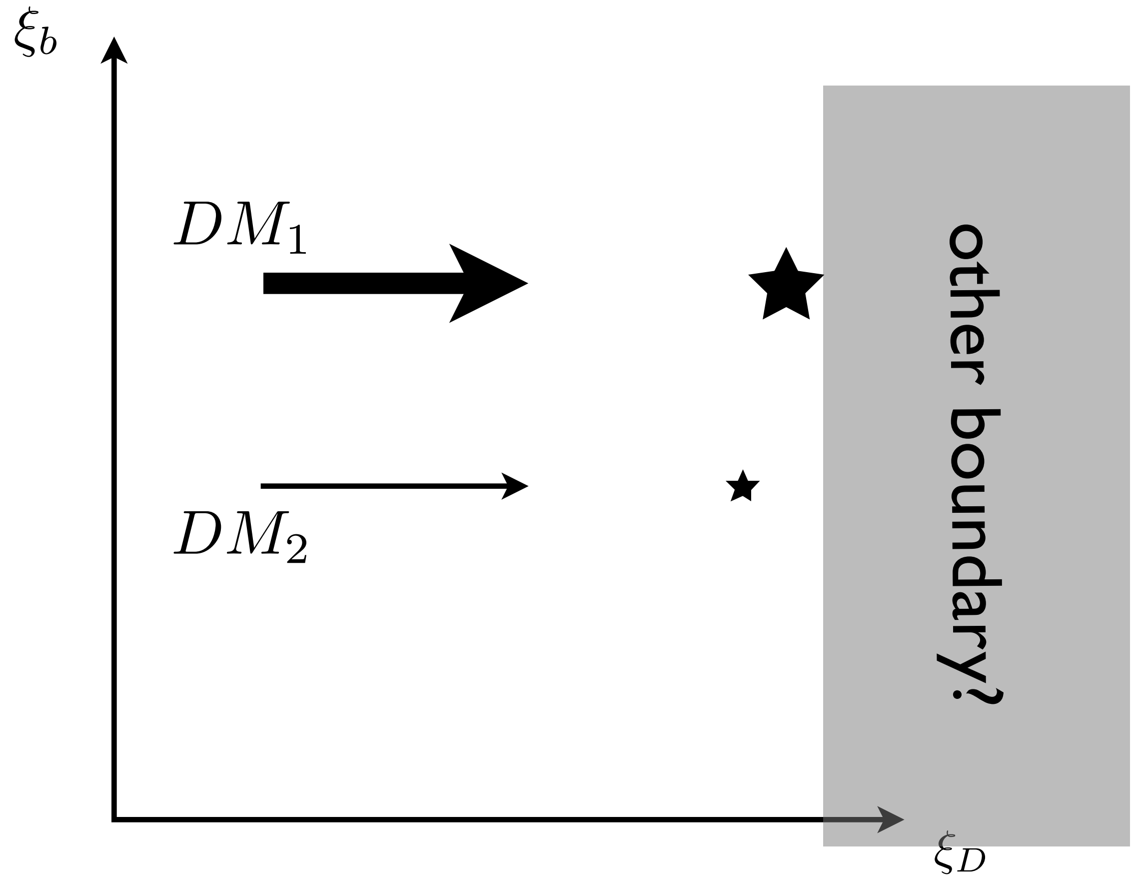
Notice that depending on the nature of the LSP, the LSS boundary can motivate a little hierarchy.

LSS boundary and multi-component DM



The LSS boundary predicts the DM to be single component

LSS boundary and multi-component DM



Single component DM: the axion

No anthropic explanation of the smallness of the QCD vacuum angle is known.

The axion solves the strong CP problem and can be the DM.

Under suitable assumptions the axion can explain the closeness of our universe to the LSS boundary.

Brief review of axion physics

The strong CP problems is solved by the coupling

i) $$\frac{\alpha_S}{8\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}_{\mu\nu}$$

ADMX and various physical processes are sensitive to the axion-photon coupling

ii) $$(\boxed{c_{UV}} - c_{IR})\frac{\alpha_{EM}}{8\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}_{\mu\nu}$$

depends on the UV model delivering the axion

The strong CP problems is solved by the coupling

i) $$\frac{\alpha_S}{8\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}_{\mu\nu}$$

ADMX and various physical processes are sensitive to the axion-photon coupling

ii) $$(c_{UV} - \boxed{c_{IR}})\frac{\alpha_{EM}}{8\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}_{\mu\nu}$$

model independent generated through axion-pion mixing

$$c_{IR} = -\frac{2}{3}\frac{4+Z}{1+Z} \qquad Z = m_u/m_d \approx 0.5$$

The strong CP problems is solved by the coupling

i) $$\frac{\alpha_S}{8\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}_{\mu\nu}$$

The zero temperature axion potential comes from the QCD chiral lagrangian after redefining i) away through a chiral rotation on the quarks

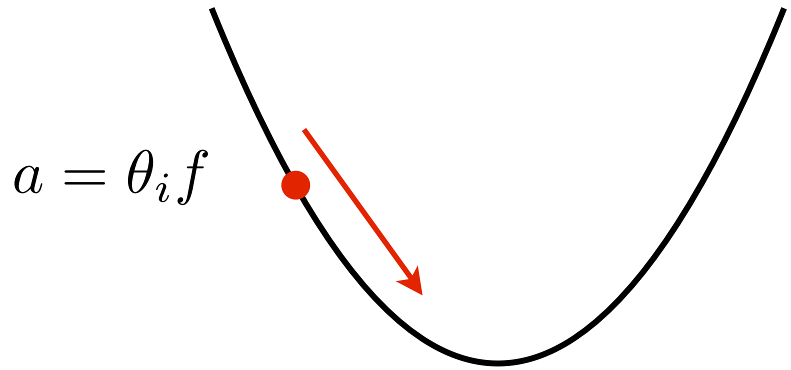
$$V(a,\pi) = \frac{f_\pi^2 m_\pi^2}{m_u + m_d}\mathrm{Tr}\left(\Sigma e^{-iQ_A a/f} M e^{-iQ_A a/f}\right) + \mathrm{h.c.} \qquad \mathrm{Tr}\, Q_A = 1$$

Q_A can be fixed to get rid of the axion-pion mixing. The axion mass is

$$m_a = \frac{m_\pi f_\pi}{f}\frac{\sqrt{Z}}{1+Z} \approx 0.6\,\mathrm{eV}\left(\frac{10^7\,\mathrm{GeV}}{f}\right)$$

Axion DM: misalignment mechanism

At high temperature (T < f) the axion field is stuck at some location in its potential



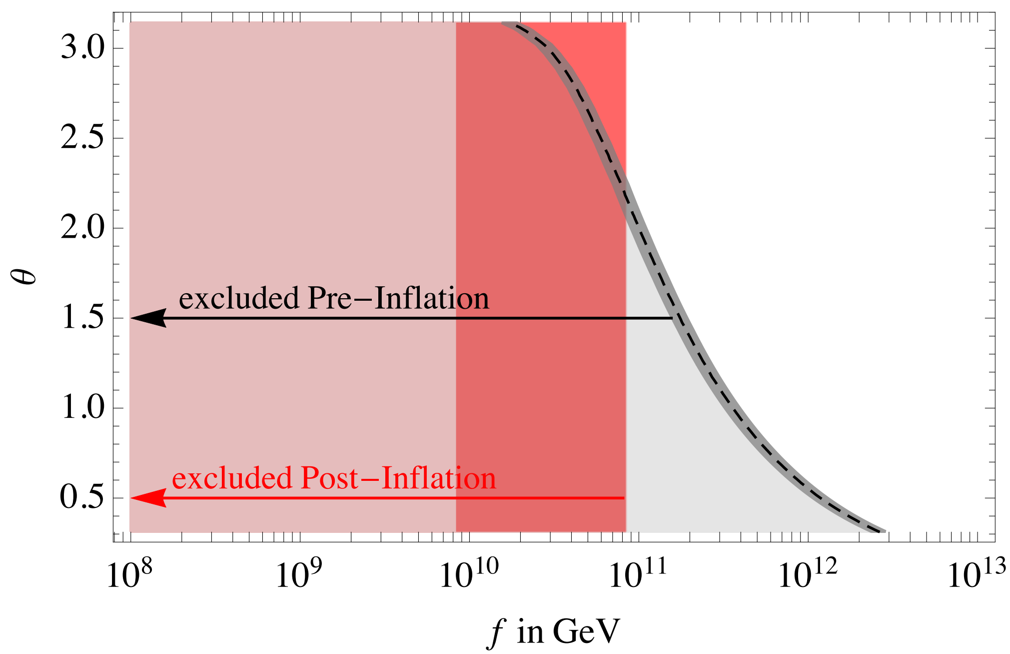
At $m_a(T_{\rm osc}) \sim H(T_{\rm osc})$ the axion starts to oscillate around its minimum and the energy density in the oscillations redshift like non-relativistic matter

$$m_a(T) \sim m_a(\Lambda_{QCD}/T)^{5.5} \;\Rightarrow\; T_{\rm osc} \sim 1\,{\rm GeV}$$

$$\xi_a = \frac{m_a}{m_a(T_{\rm osc})}\frac{\rho_a(T_{\rm osc})}{s(T_{\rm osc})} \approx 1.7\,\xi_{D0}\,\theta^2\left(\frac{f}{10^2\,{\rm GeV}}\right)^{1.18}$$

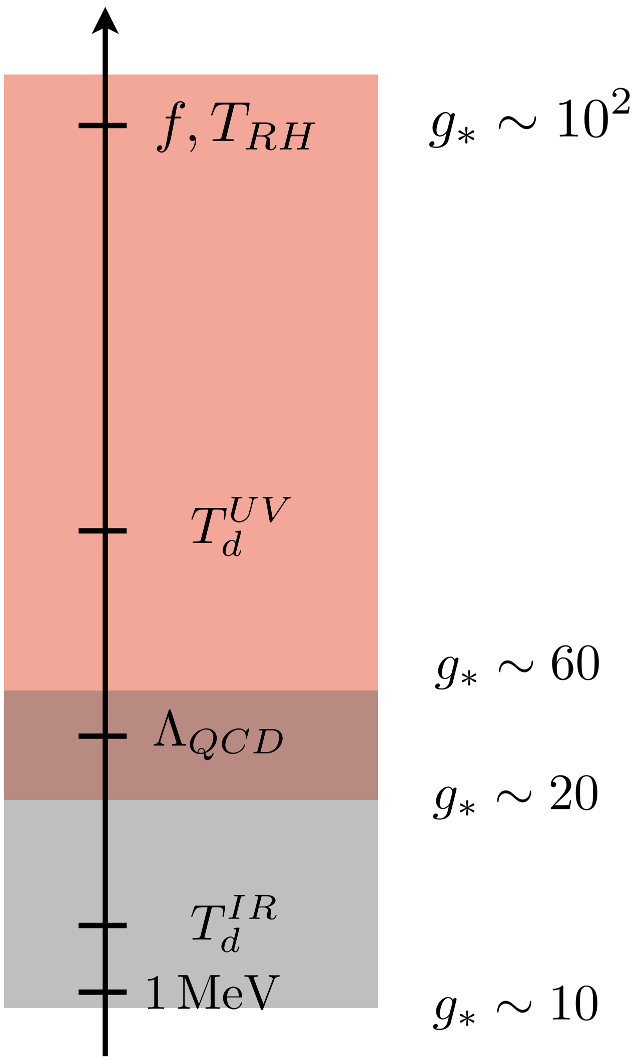
If the PQ is broken during inflation and is not restored after reheating θ takes a random value in our Hubble patch between 0 and π. On the other hand θ is averaged over the patch and $\theta_{\rm eff} = \pi/\sqrt{3}$

Kim et al ('08)



Axion production from decay of topological defects should be included. This can lower f by an order of magnitude.

Axion DM: thermal production



Above the QCD PT axions are kept in equilibrium with the plasma through their interactions with gluon.

$$f \gtrsim 10^6\,\mathrm{GeV} \Rightarrow T_d^{UV} \gtrsim \Lambda_{QCD}$$

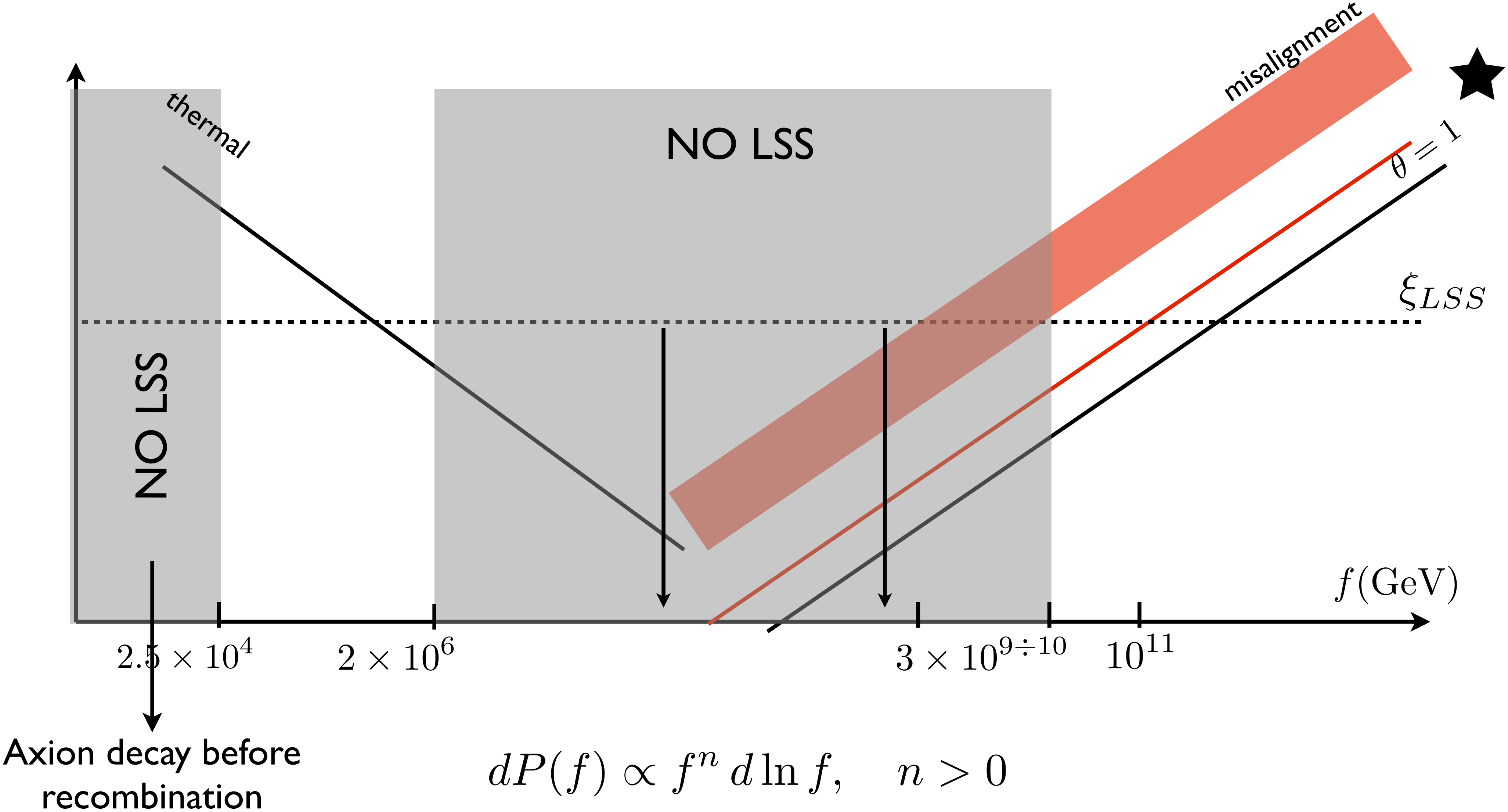
Below the QCD PT the axion interacts with pions (ππ→πa) and nucleons (Nπ→Na).

$$f \sim 10^7\,\mathrm{GeV} \Rightarrow T_d^{IR} \sim \text{few MeV}$$

$$\xi_a = m_a \frac{g_*(T_0)/2}{g_*(T_d^{IR})} \approx 1.1\,\mathrm{eV}\frac{10^6\,\mathrm{GeV}}{f}$$

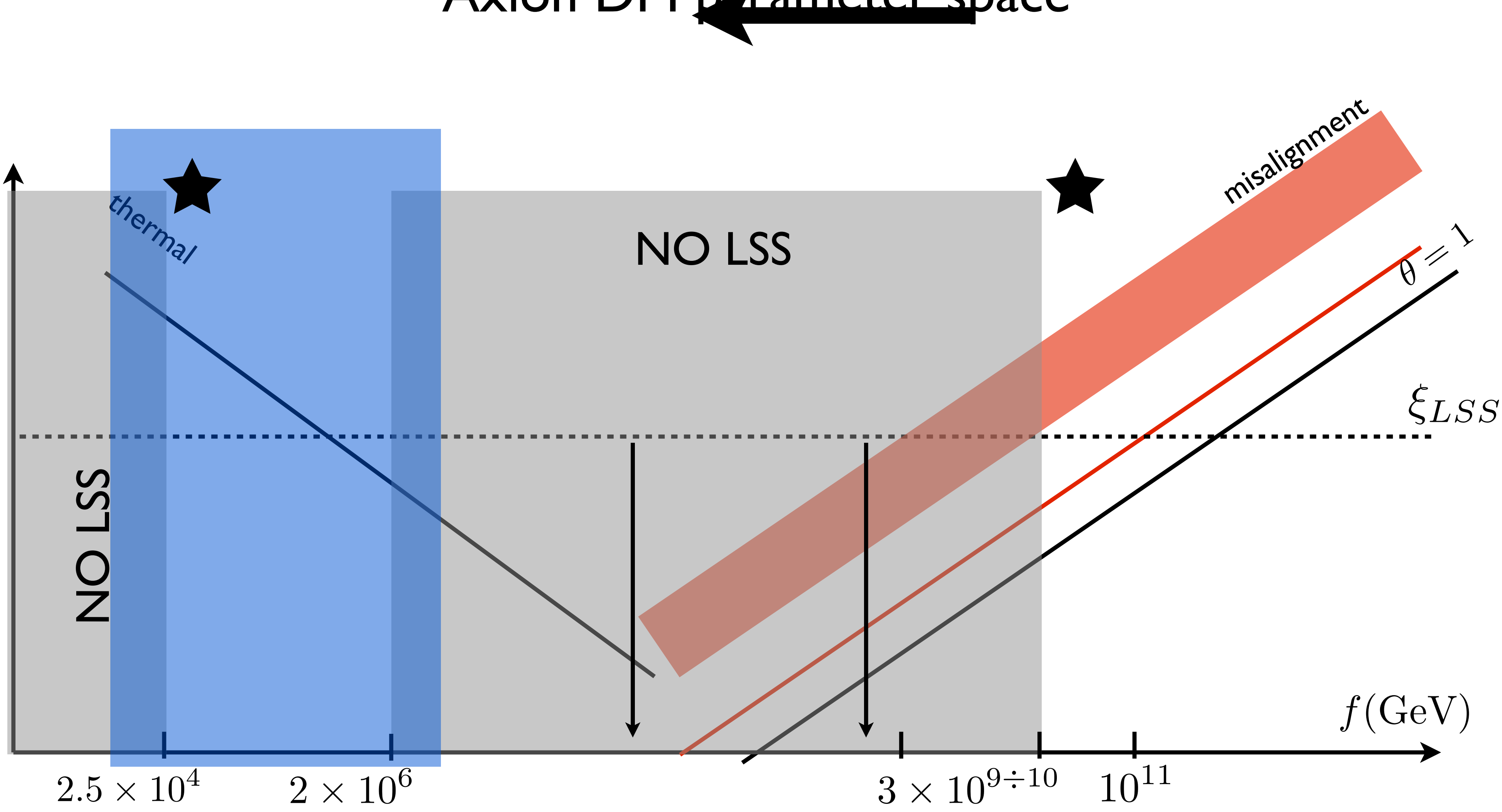
$$\Gamma(a \to \gamma\gamma) = c^2 \frac{\alpha_{EM}^2}{256\pi^3}\frac{m_a^3}{f^2} \quad \longrightarrow \quad \frac{1}{t_{\mathrm{rec}}^2} \sim \frac{\xi_a T_{\mathrm{rec}}^3}{M_{Pl}^2}$$

Axion DM parameter space



$$dP(f) \propto f^n \, d\ln f, \quad n > 0$$

Axion DM parameter space



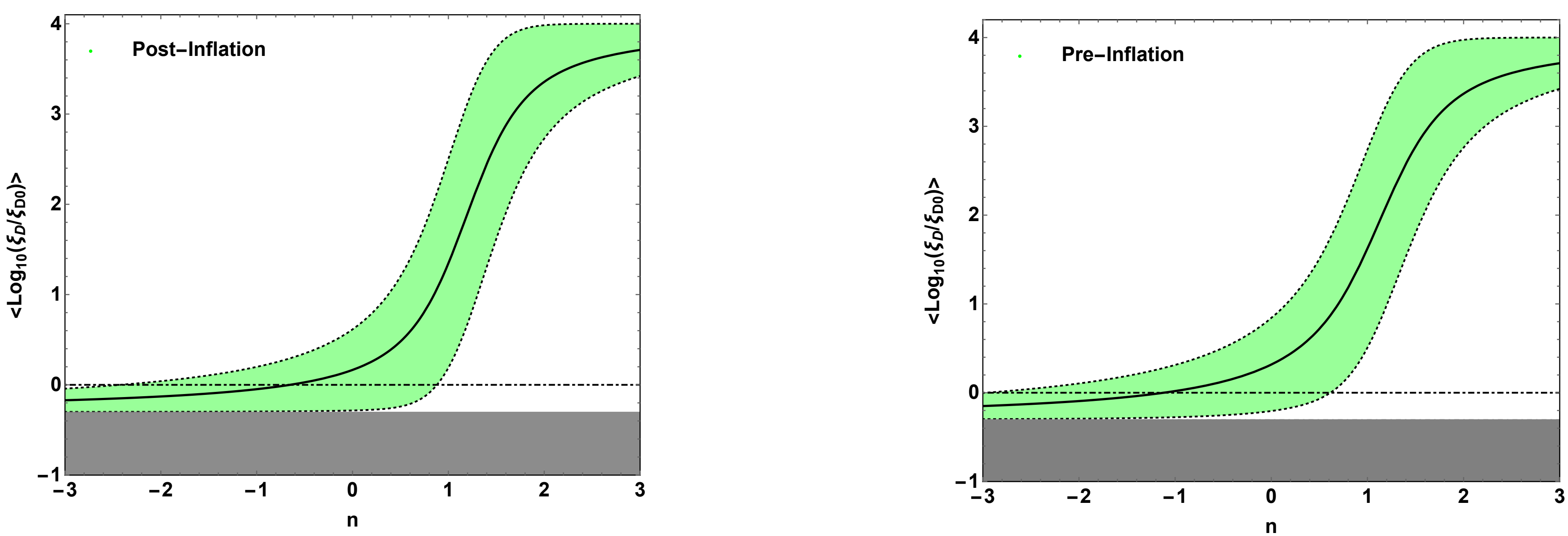
$$dP(f) \propto f^n \, d\ln f, \quad n < 0$$

The thermal axion window is likely not allowed by a variety of constraints: free-streaming of LSS by axion hot dark matter, large rate of axion emission by stars.

$$dP \propto \theta(\xi_D - \xi_c)\boxed{\frac{1}{1+\xi_D/\xi_{b0}}} f^n d\log f\ (d\theta) \qquad \xi_c = 0.5\,\xi_{D0}$$

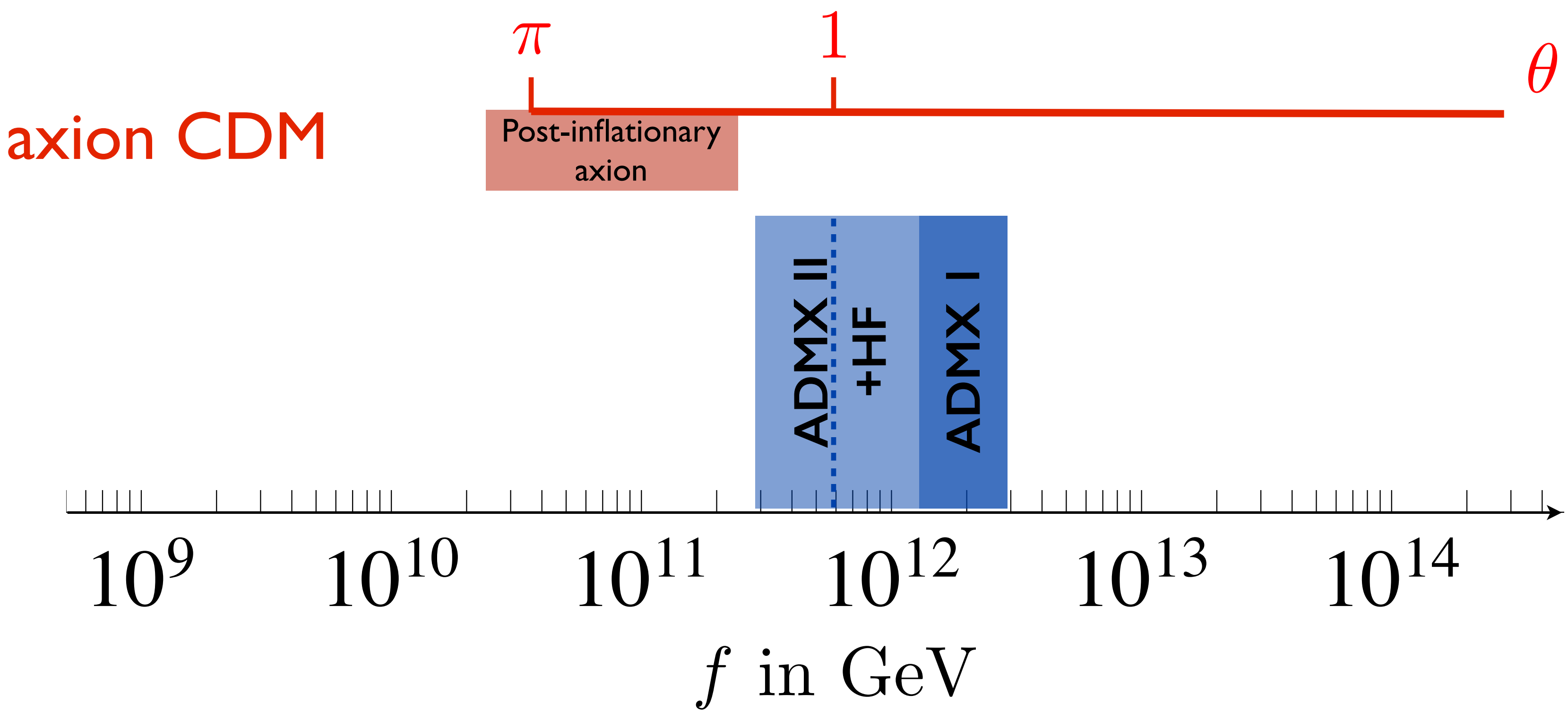
Causal Patch dilution of observers if they are made of baryons

Freivogel ('08)



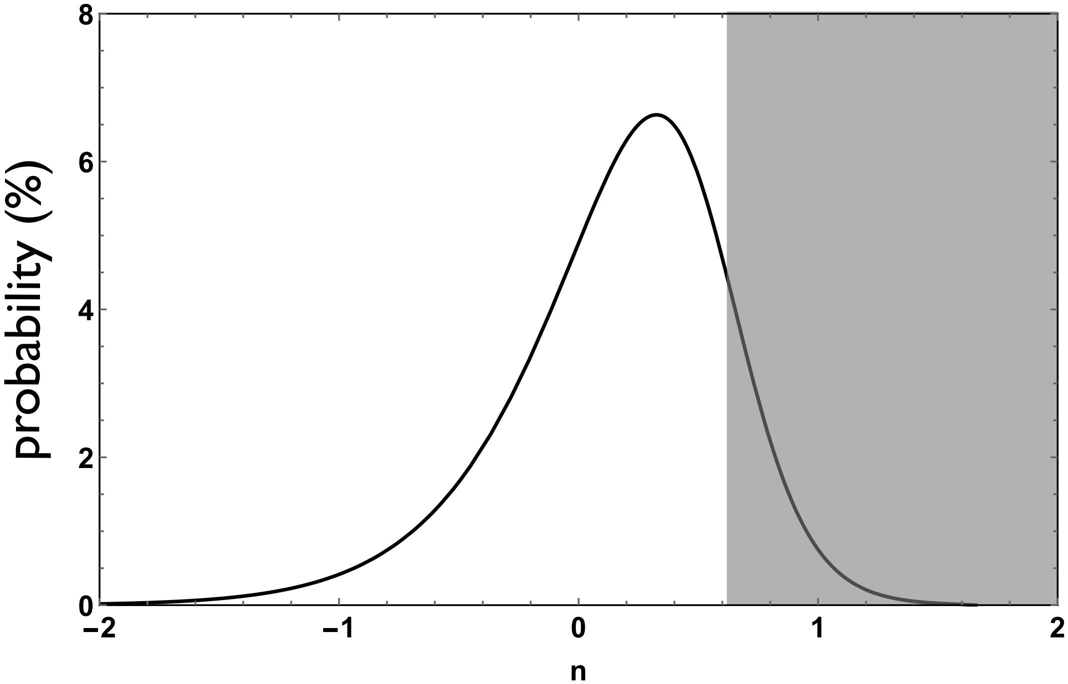
$$\theta_{\min} = 10^{-2} < \theta < \pi$$

$$\xi_c < \xi_D < \xi_{\max} = 10^4$$

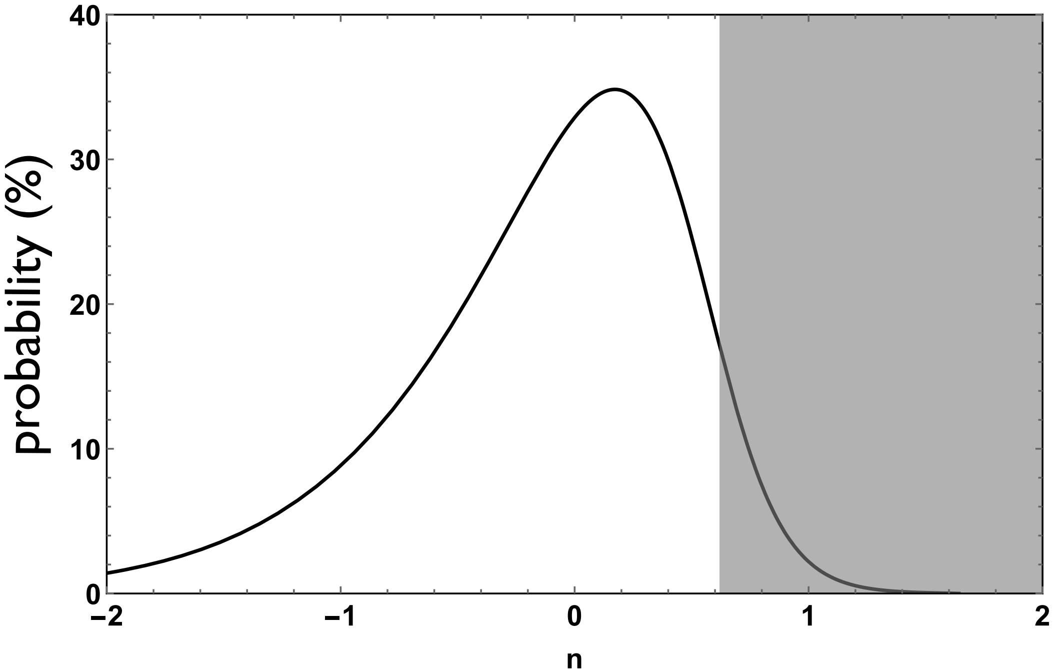


axion CDM
π
1
θ
Post-inflationary axion
ADMX II
+HF
ADMX I
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
f in GeV

ADMX I



ADMX II



"The Definitive Search for Dark Matter Axions"

ADMX

the Axion Dark Matter eXperiment

A model & the Higgs mass

Ingredients

Axion

The multiverse motivates the existence of a solution to the strong CP problem. If we live close to the LSS boundary for a dynamical reason then the axion is likely to be DM.

Supersymmetry

Ameliorate the fine tuning of both the EW and CC hierarchies.

Provides a zeroth-order understanding of why the Higgs quartic coupling is small.

aMSSM

To the matter content of the MSSM add a singlet chiral superfield, coupled through

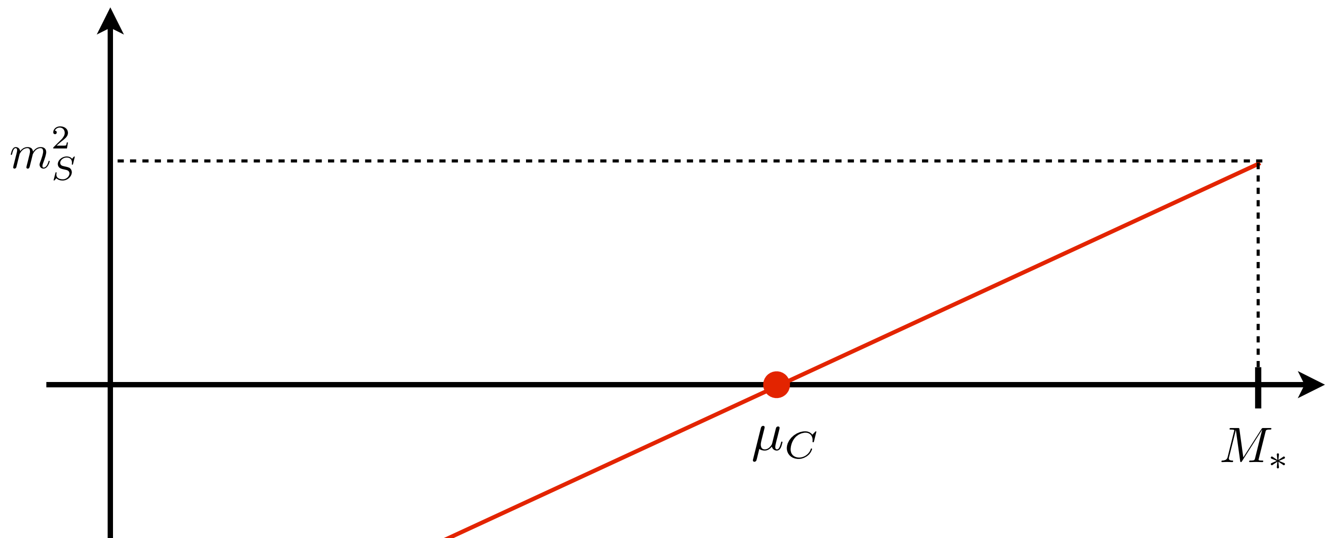
$$W = \xi S H_1 H_2 \qquad\qquad V_{\rm soft} = \xi A_\xi S H_1 H_2 + m_S^2 |S|^2$$

$$m_S^2 > 0$$

The model has an exact global PQ symmetry which has a color anomaly. Simplest supersymmetric DFSZ model. The model has domain wall number 3.

At tree level both the PQ and EW symmetry are unbroken.

$$
\begin{aligned}
16\pi^2 \frac{d\xi}{dt} &= 4\xi^3 + O(\xi y_t^2) \\
8\pi^2 \frac{dm_{1,2}^2}{dt} &= \xi^2 (m_1^2 + m_2^2 + m_S^2 + A_\xi^2) + O(y_t^2) \\
8\pi^2 \frac{dm_S^2}{dt} &= 2\xi^2 (m_1^2 + m_2^2 + m_S^2 + A_\xi^2) \\
8\pi^2 \frac{dA_\xi}{dt} &= 4\xi^2 A_\xi + O(y_t^2)
\end{aligned}
$$



$$\mu_C \sim \xi \langle S \rangle \sim M_* e^{-4\pi^2/\xi^2}$$

PQ is broken spontaneously and radiatively. The dynamically generated scale is **a priori** independent of the absolute normalization of the soft masses.

LSS boundary: $\xi = O(1) \Rightarrow \mu_C \gg v$

$$\mathcal{M}_H^2 \approx \begin{pmatrix} \mu_C^2 + m_2^2 & A_\xi \mu_C \\ A_\xi \mu_C & \mu_C^2 + m_1^2 \end{pmatrix}$$

EWSB with high scale SUSY: $\det\, \mathcal{M}_H^2 \sim -m_Z^2 \tilde{m}^2$

$\mu_C \gg \tilde{m}:$ $\det\, \mathcal{M}_H^2 \sim \mu_C^4$ NO EWSB

$\mu_C \ll \tilde{m}:$ $\det\, \mathcal{M}_H^2 \sim \pm \tilde{m}^4$ NO EWSB

EWSB forces: $\mu_C \sim \tilde{m}$

A very concrete manifestation of the μ problem in this setup.
It has an anthropic solution.

$$V(S) = \Lambda(\mu) + m_S^2 |S(\mu)|^2 + V^{(1)}(S;\mu) + \ldots \qquad \text{1-loop}$$

Expand around the point μC where the S soft mass vanishes. The leading log expansion of V then works fine.

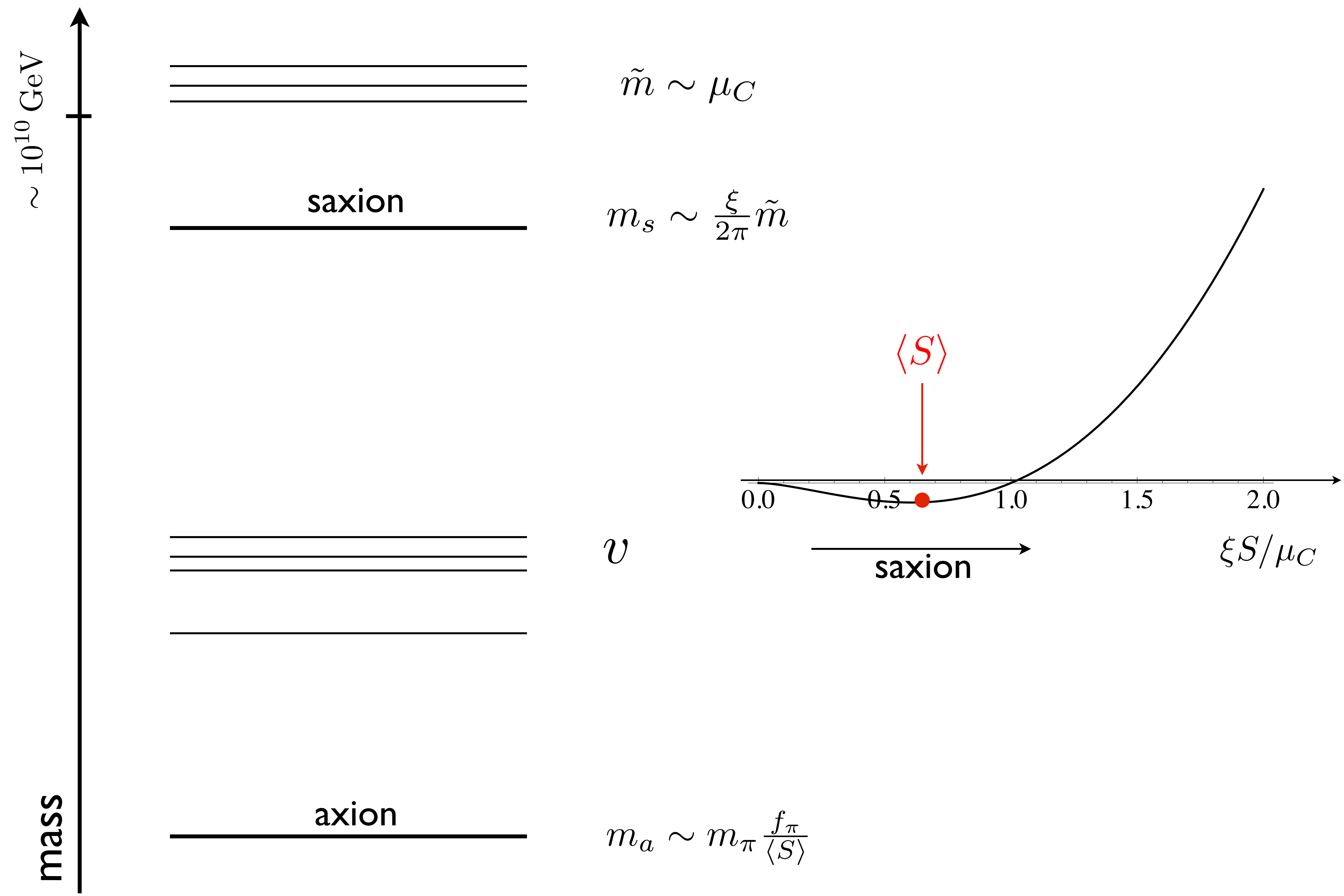
$$V(S) = \frac{1}{64\pi^2}\left[4m_H^4\left(\log\frac{m_H^2}{\mu_C^2} - \frac{3}{2}\right) + 4m_h^4\left(\log\frac{m_h^2}{\mu_C^2} - \frac{3}{2}\right) - 8m_F^4\left(\log\frac{m_F^2}{\mu_C^2} - \frac{3}{2}\right)\right]$$

$$\begin{aligned} m_{H,h}^2 &= \frac{m_1^2 + m_2^2}{2} + \xi^2|S|^2 \pm \sqrt{\frac{(m_1^2 - m_2^2)^2}{2} + \xi^2 A_\xi^2 |S|^2} \\ m_F &= \xi|S| \end{aligned}$$

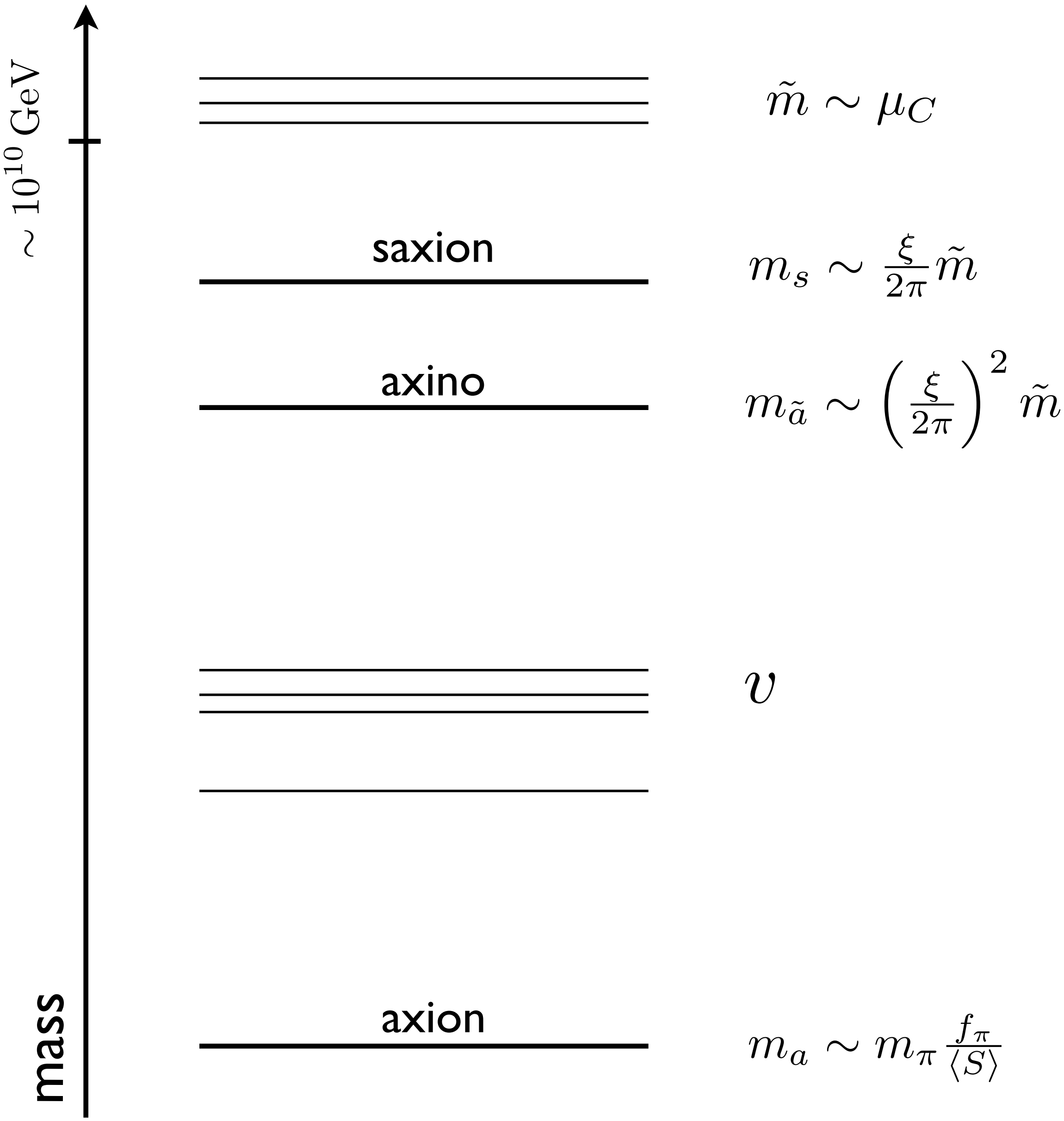
Inputs: $m_1, \quad m_2, \quad A_\xi, \quad \mu_C, \quad \xi$

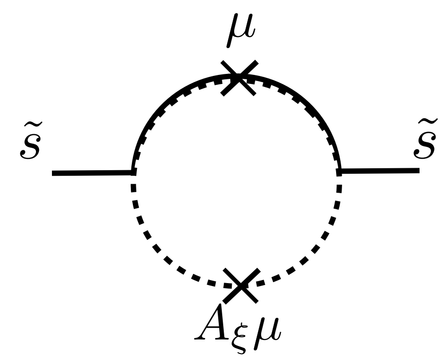
Outputs: $\det \mathcal{M}_H^2, \quad \tan\beta, \quad f, \quad A_{SHH}$

The spectrum around H=0



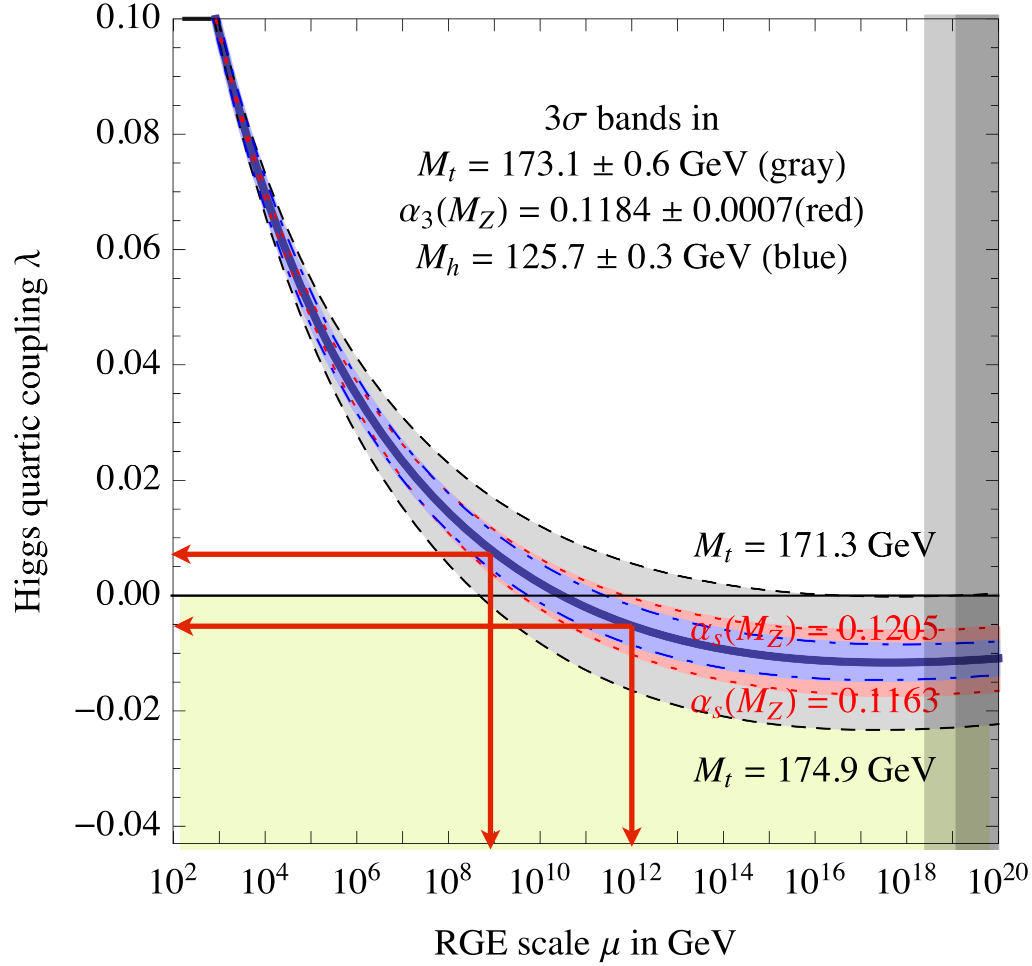
The spectrum around H=0





The Higgs quartic around H=0

$$V_{SM}(H) = \lambda_{SM}|H|^4$$



Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia ('13)

The Higgs quartic around H=0

$$V_{SM}(H) = \lambda_{SM}|H|^4$$

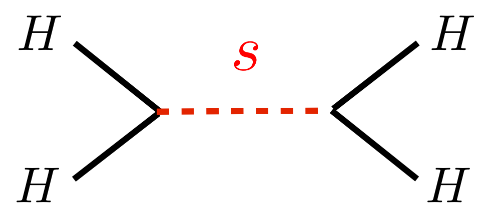
$$\lambda_{SM} = \frac{g^2+g'^2}{8}\cos^2 2\beta + \frac{\xi^2}{4}\sin^2 2\beta - \boxed{\frac{\xi^2\mu^2}{6\,m_s^2}\left(1-\frac{A_\xi}{2\mu}\sin 2\beta\right)^2}$$

MSSM D-terms

F-term

saxion contribution

$$\tan\beta \sim 1$$



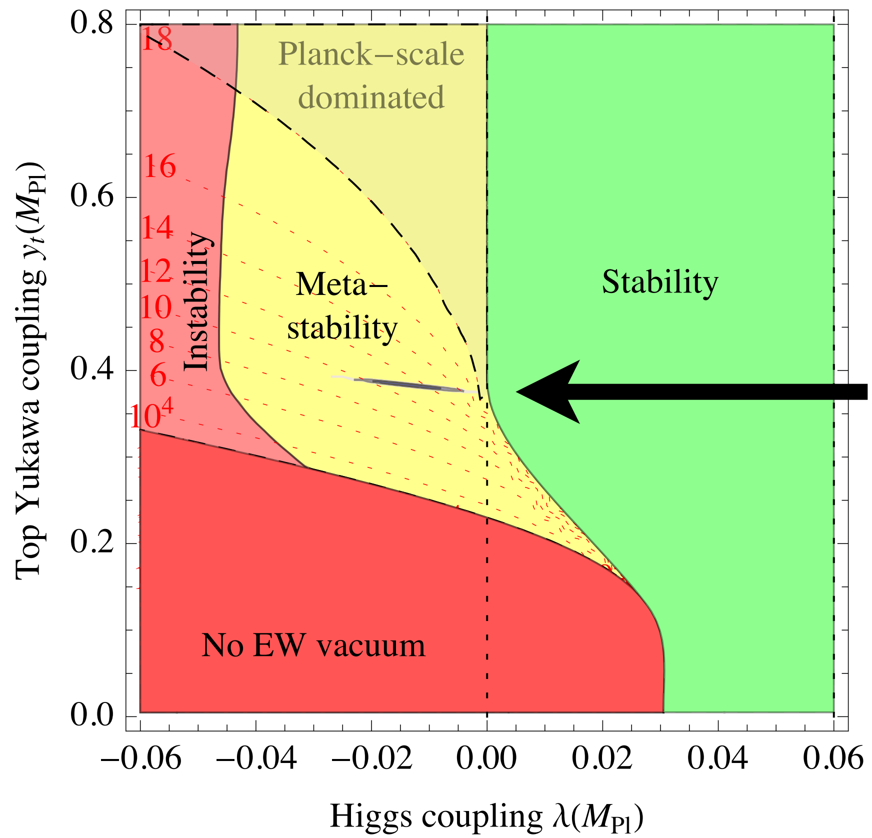
The saxion mass is one-loop below the other sparticles. Integrating it out gives a large and negative contribution to the Higgs quartic coupling. The H=0 vacuum is unstable.

$$\Delta\lambda_{SM} \sim -16\pi^2$$

From the anthropic point of view this contribution HAS to be tuned away to allow for our vacuum to exist.

Solid anthropic lower bound on λ from vacuum stability

$$\lambda_{SM}(M_*) > \lambda_{\text{crit}} \approx -0.04$$



Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia ('13)

We are pushed against the instability boundary for λ.
Anthropic explanation for the existence of a heavy quark?

A postdiction for the Higgs mass?

$$\lambda_{SM} = \lambda_+ - 16\pi^2\epsilon^2 \qquad\qquad \lambda_+ \approx \frac{\xi^2}{4}$$

Assuming a featureless cancellation in the A_{SHH} trilinear the pdf for ϵ is known

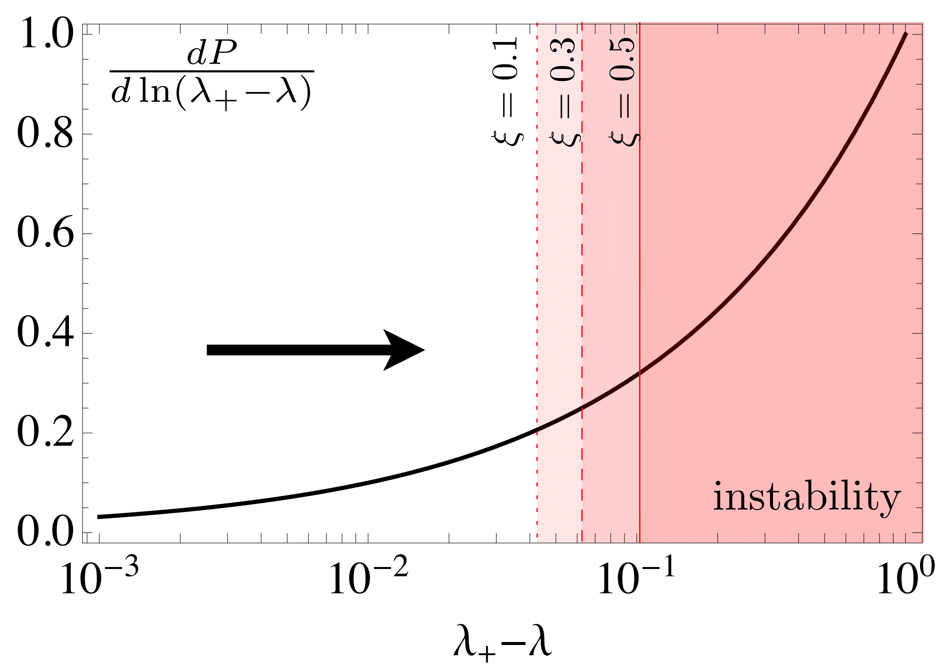
$$dP(\epsilon) \propto d\epsilon$$

This allows to calculate the pdf for the Higgs quartic as a function of ξ

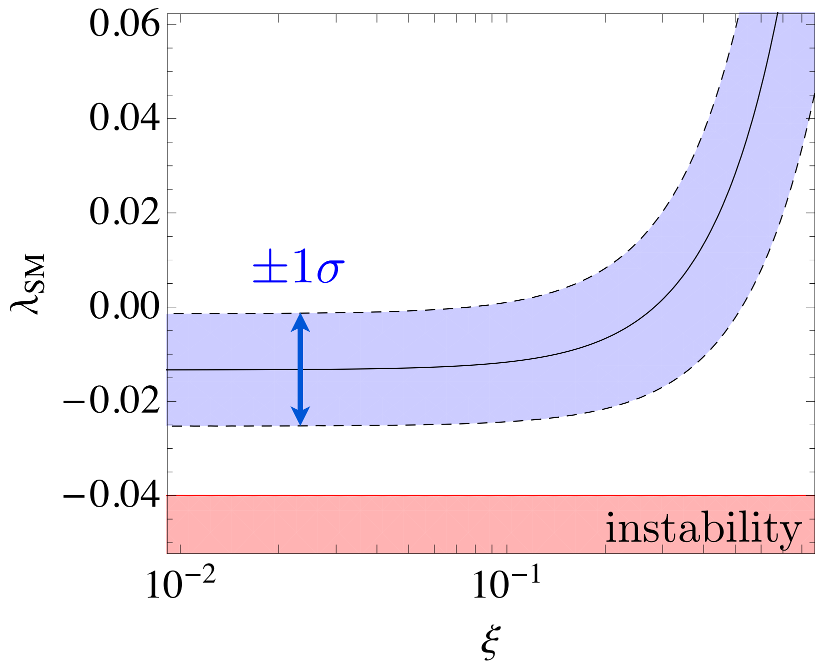
$$dP(\lambda) \propto \frac{d\lambda}{(\lambda_+ - \lambda)^{1/2}}$$

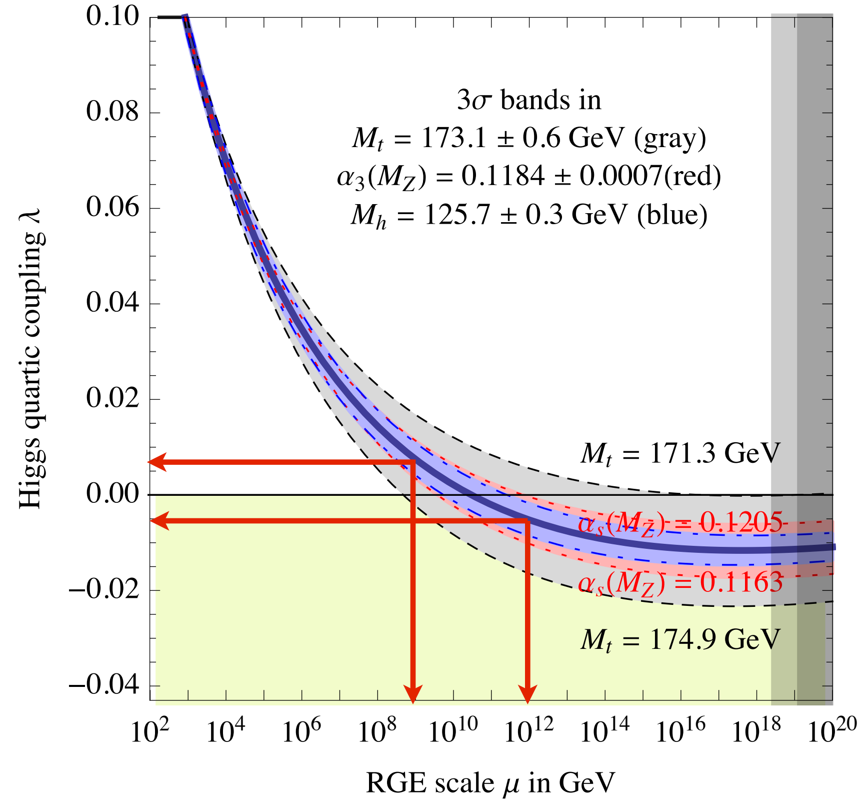
The probability force is mild:

$$\frac{d\ln P}{d\ln(\lambda_+ - \lambda)} = \frac{1}{2}$$



$$\langle \lambda_{SM} \rangle = \frac{1}{3}\lambda_{\rm crit} + \frac{2}{3}\lambda_{+} \qquad \sigma_{\lambda_{SM}} = \frac{2}{3\sqrt{5}}|\lambda_{+} - \lambda_{\rm crit}|$$





λ<0.8 to have a perturbative theory up to the Planck scale

Due to dimensional transmutation the a priori pdf for f is expected to be almost flat in log scale. Its posterior pdf will be determined by the the a priori pdf for the soft SUSY breaking scale due to the EW tuning

$$f \sim \tilde{m}$$

$$dP(\tilde{m}) \propto \tilde{m}^{\alpha} d \ln \tilde{m} \longrightarrow dP(f) \propto \boxed{\frac{v^2}{f^2}} f^{\alpha} d \ln f$$

EW tuning

In particular the previous discussion about the scanning of f applies to this case setting

$$n = \alpha - 2$$

A model with low scale SUSY?

To the matter content of the MSSM add a singlet chiral superfield, coupled through

$$W = \frac{1}{M_*} S^2 H_1 H_2$$

Add KSVZ field to cure both domain wall problems and to drive the S soft mass negative.

work in progress…

Conclusions

→ The observed DM and baryon abundances could be selected by the LSS boundary.

In case of LSP DM the LSS boundary can explain a little SUSY hierarchy. ←

→ If the strong CP problem is solved by an axion then it is likely to be the DM.

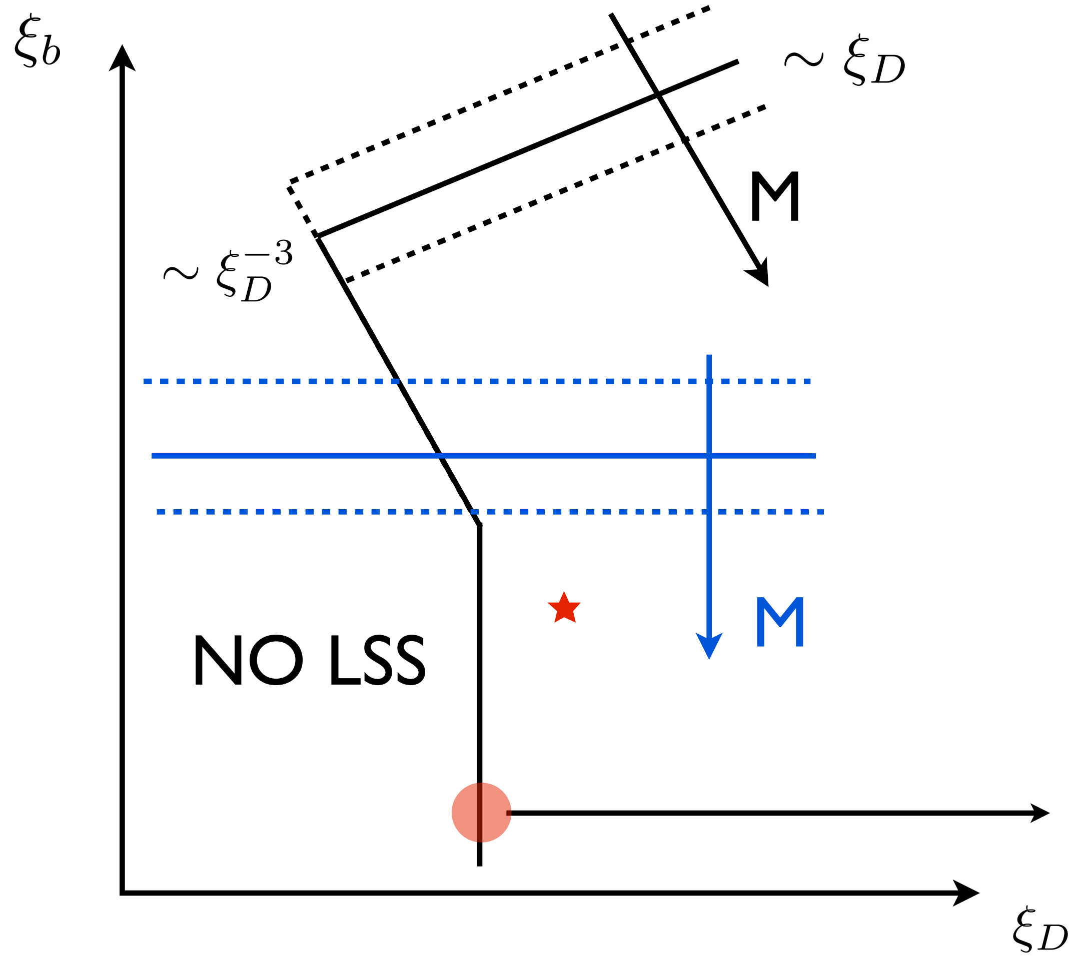
ADMXII is not going to probe such an axion in the post-inflationary case and unlikely so in the pre-inflationary case. ←

→ The multiverse approach revive models which would be otherwise not be considered.

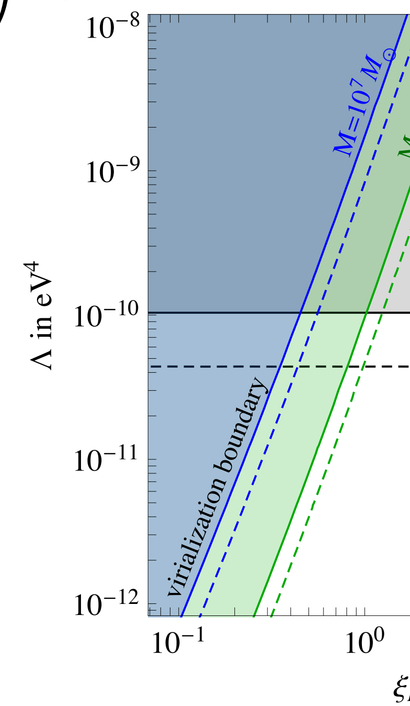
BACKUP

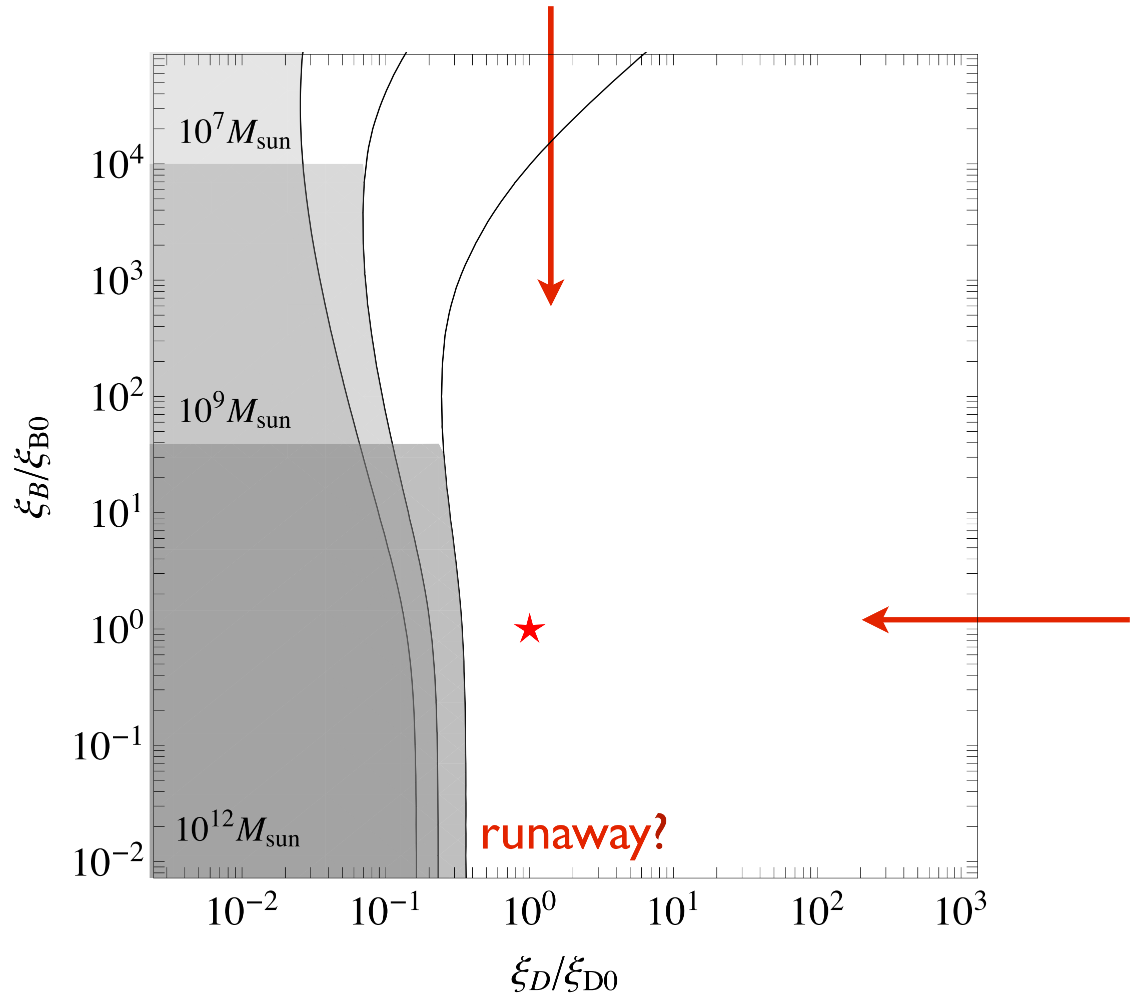
The value of the CC could be determined by causal diamond measure. What about the DM density?

$$\delta(M) \sim \frac{\min(T_{\rm eq}, T_{\rm hor})}{T_\Lambda}\left(\frac{\xi_b}{\xi_m} e^{-(M_S/M)^{2/3}} + \frac{\xi_D}{\xi_m} G(M)\right)\delta_0$$



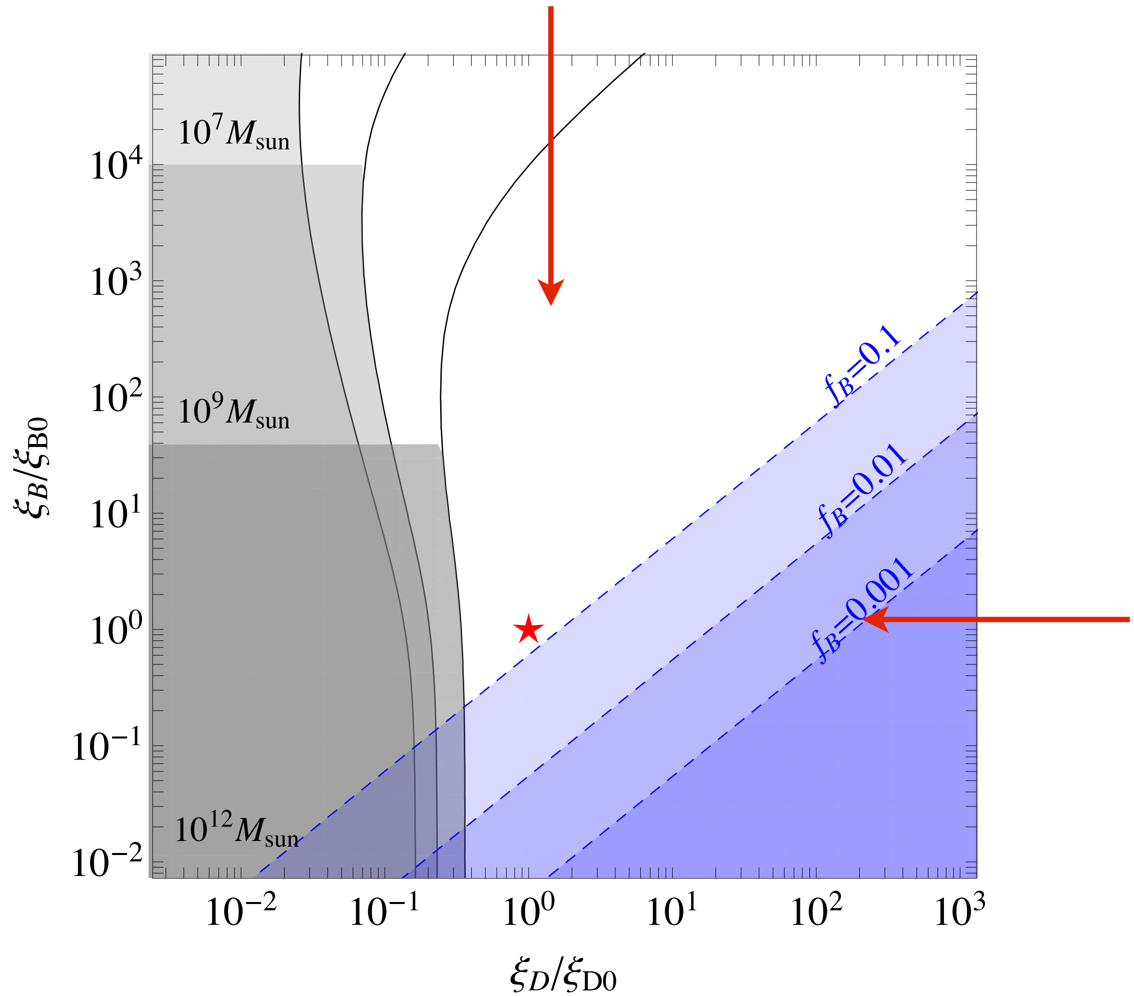
$\delta \sim \xi_D^{4/3}/\Lambda^{1/3}$





Assumption:

the vicinity of the LSS boundary is determined by multiverse dynamics



Assumptions:

Observers are made of baryons and observations occur after radiation domination.
Probabilities must then be weighted by the number of baryons which scales as

$$N_b \propto \frac{1}{1+\xi_D/\xi_b}$$

Freivogel ('08)